Hierarchical, High Fidelity Modeling and Simulation of Static and Dynamic Behaviour of Soil Structure Systems

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Outline

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Motivation

Improve modeling and simulation for infrastructure objects

Use of high fidelity numerical models to analyze behavior of soil structure systems

Reduction of modeling uncertainty, ability to perform high(er) level of sophistication modeling and simulation

Accurately follow the flow of input and dissipation of energy in a soil structure system

Development of an expert, rational physics based, system for modeling and simulation

Hypothesis

- Interplay dynamic characteristics of the Dynamic Forcing / Earthquake, Soil/Rock and Structure in time domain, plays a decisive role in successes and failures
- Timing and spatial location of energy dissipation determines location and amount of damage
- If timing and spatial location of the energy dissipation can be controlled (directed), we could optimize soil structure system for
  - Safety and
  - Economy

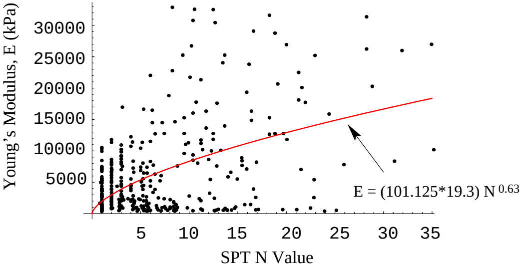
Predictive Capabilities

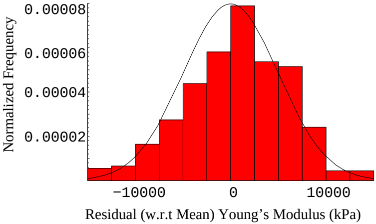
- Prediction under Uncertainty: use of computational model to predict the state of SSI system under conditions for which the computational model has not been validated.
- Verification provides evidence that the model is solved correctly. Mathematics issue.
- Validation provides evidence that the correct model is solved. Physics issue.
- Modeling and parametric uncertainties are always present, need to be addressed
- Predictive capabilities with low Kolmogorov Complexity
- Goal: Predict and Inform and not (force) Fit

Modeling Uncertainty

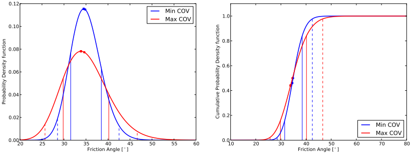
- Simplified modeling: Features (important ?) are neglected (6D ground motions, inelasticity)
- Modeling Uncertainty: unrealistic and unnecessary modeling simplifications
- Modeling simplifications are justifiable if one or two level higher sophistication model shows that features being simplified out are not important

Parametric Uncertainty: Material Stiffness

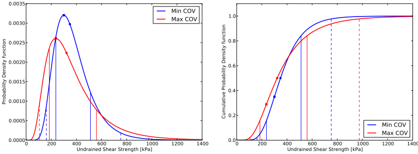




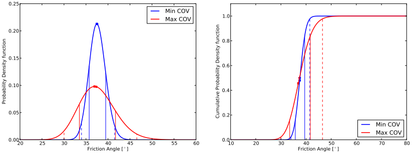
Parametric Uncertainty: Material Properties



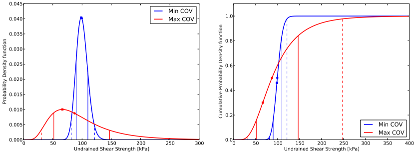
Field ϕ



Field c_u



Lab ϕ



Lab c_u

Realistic ESSI Modeling Uncertainties

- Seismic Motions: 6D, inclined, body and surface waves (translations, rotations); Incoherency
- Inelastic material: soil, rock, concrete, steel; Contacts, foundation–soil, dry, saturated slip–gap; Nonlinear buoyant forces; Isolators, Dissipators
- Uncertain loading and material
- Verification and Validation $\Rightarrow$ Predictions

Outline

Real ESSI Simulator System

The Real ESSI, **<u>Real</u>**istic modeling and simulation of **<u>E</u>**arthquakes, **<u>S</u>**oils, **<u>S</u>**tructures and their **<u>I</u>**nteraction. Simulator is a software, hardware and documentation system for high fidelity, high performance, time domain, nonlinear/inelastic, deterministic or probabilistic, 3D, finite element modeling and simulation of:

- statics and dynamics of soil,
- statics and dynamics of rock,
- statics and dynamics of structures,
- statics of soil-structure systems, and
- dynamics of earthquake-soil-structure system interaction

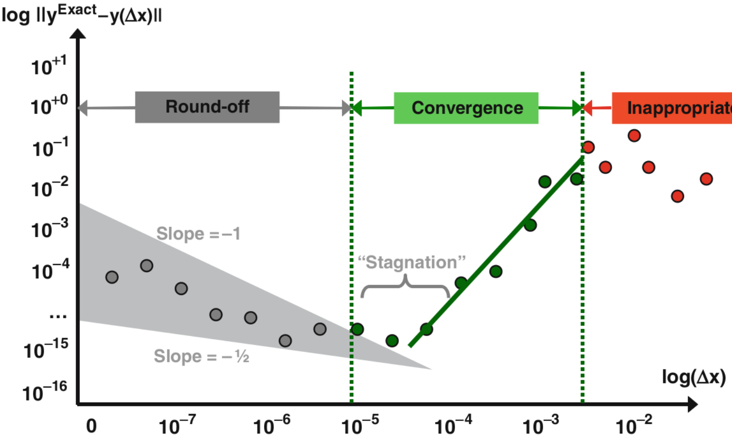
Real ESSI Simulator System

- Real ESSI System Components
  - Pre-processor (gmsh/gmESSI, X2ESSI, SASSI2ESSI)
  - Simulator (local, remote/cloud)
  - Post-Processor (Paraview, Python, Matlab)
- Real ESSI System availability:
  - Professional Practice and Educational Institutions: Amazon Web Services (AWS, economical!)
  - Government Agencies, National Labs and some Companies: Local/Remote
- Real ESSI Education and Training
- System description and documentation at `http://real-essi.us/`

Quality Assurance

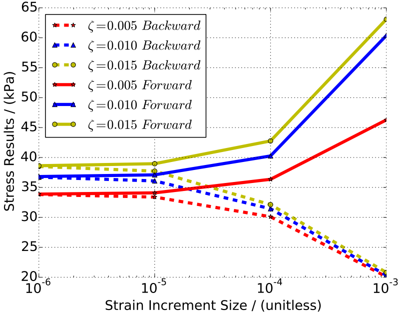
- Full verification suit for each element, model, algorithm
- Certification process in progress for NQA-1 and ISO-90003-2014

High Fidelity (Parametric, Geometric and Algorithmic)



Example: Verification for Elastoplastic Algorithms

Comparison between forward and backward Euler algorithms.



Drucker-Prager Non-Associate Material with Backward Euler Algorithm

ξ	0.05	0.10	0.15
Observed β	0.892	0.870	0.858
GCI	0.23%	0.33%	0.41%
Result(Pa)	33816.496	36714.681	38499.480
Uncertain(Pa)	±77.673	±121.912	±156.082
Richarson(Pa)	33878.635	36812.210	38624.345

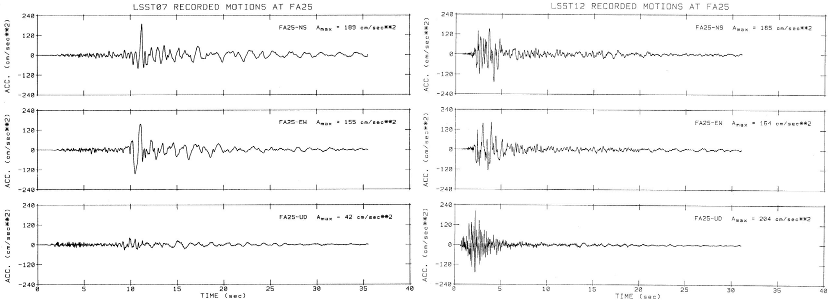
Drucker-Prager Non-Associate Material with Forward Euler Algorithm

ξ	0.05	0.10	0.15
Observed β	1.040	1.049	1.054
GCI	0.08%	0.09%	0.11%
Result(Pa)	33887.813	36818.553	38627.278
Uncertain(Pa)	±25.944	±34.672	±40.695
Richarson(Pa)	33867.058	36790.815	38594.722

Outline

3D (6D) Seismic Motions

- All (most) measured motions are full 3D (6D)
- One example of an almost 2D motion (LSST07, LSST12)

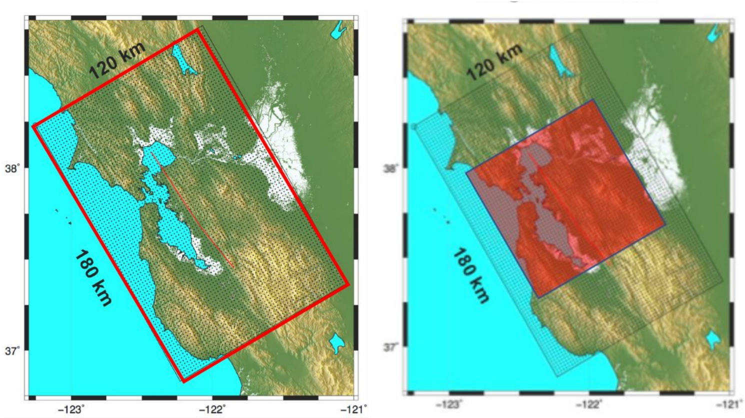


- 1D (?): M 6.9 San Pablo, Guatemala EQ, 14Jun2017

Regional Geophysical Models

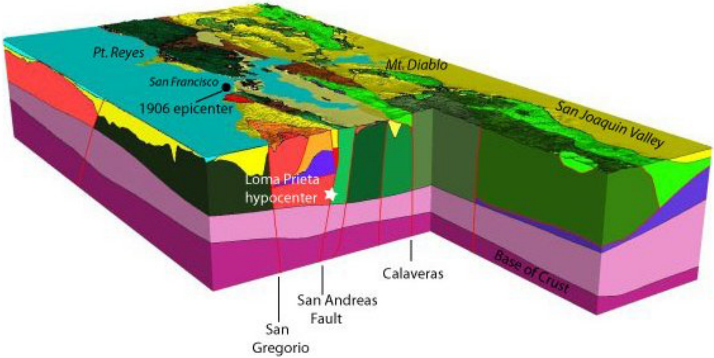
- High fidelity free field seismic motions on regional scale
- Knowledge of geology (deep and shallow) needed
- High Performance Computing using SW4 on CORI (LBNL)
- Collaboration with LLNL: Dr. Rodgers, Dr. Pitarka and Dr. Petersson

Regional Geophysical Models



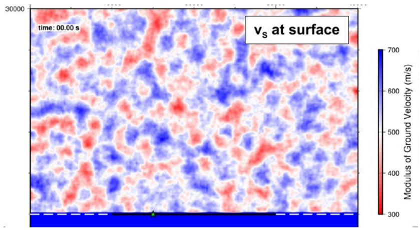
Rodgers and Pitarka

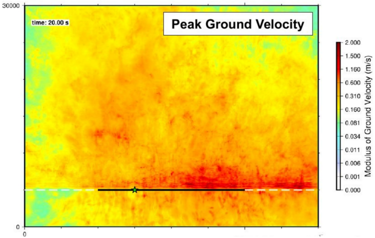
Regional Geophysical Models



USGS

Example Regional Model





Example Regional Model (Rodgers)

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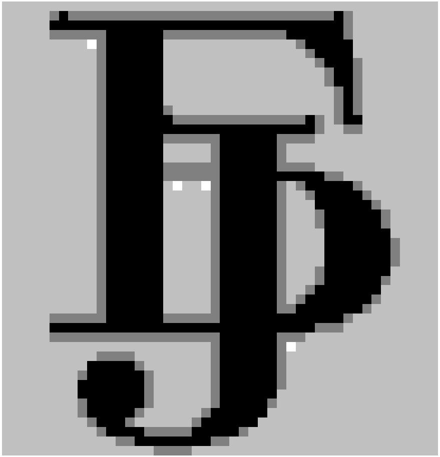
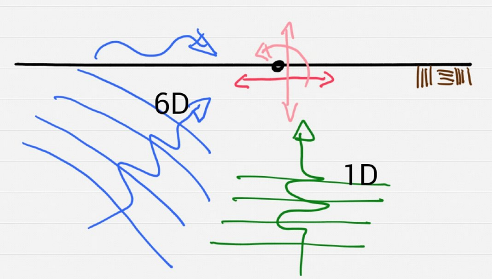


ESSI: 6D or 1D Seismic Motions

- Assume that a full 6D (3D) motions at the surface are only recorded in one horizontal direction
- From such recorded motions one can develop a vertically propagating shear wave in 1D
- Apply such vertically propagating shear wave to the same soil-structure system



6D Free Field Motions (closeup)

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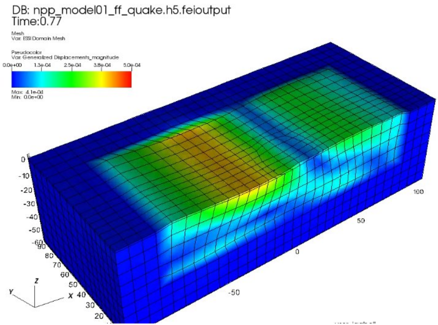
1D vs 3D Seismic Motions

- One component of motions (1D) from 3D
- Excellent fit



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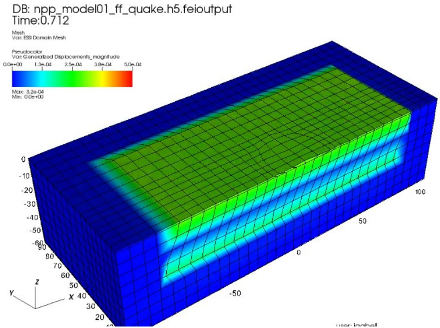

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6D vs 1D NPP ESSI Response Comparison

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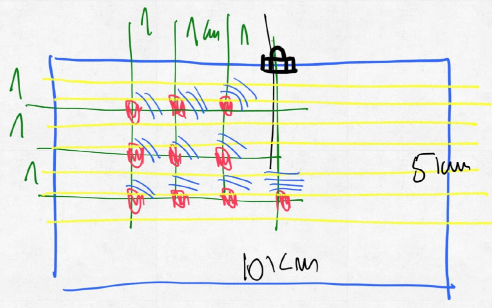
Outline

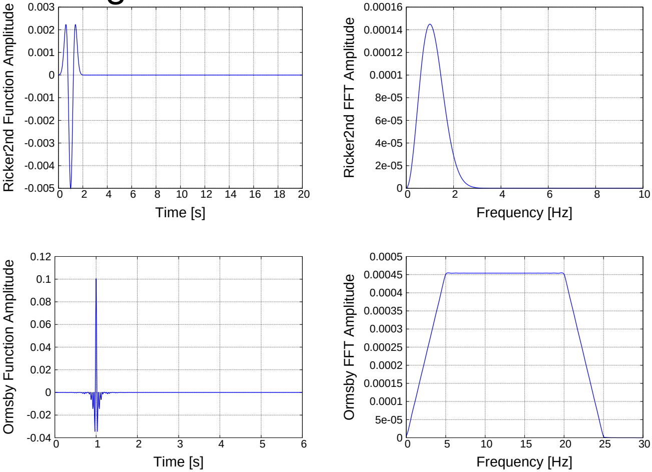
Stress Testing SSI Systems

- Excite SSI system with a suite of seismic motions
- Simple sources, variation in strike and dip, P and S waves, surface waves (Rayleigh, Love, etc.)
- Stress test soil-structure system
- Try to "break" the system, shake-out strong and weak links



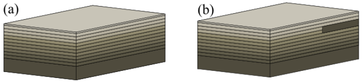
Stress Test Source Signals

- Ricker
- Ormsby

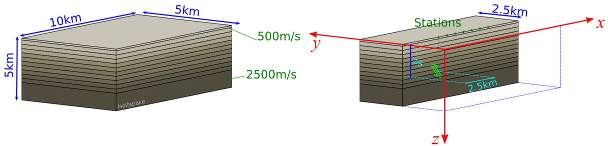


Layered and Dyke/Sill Models

- (a) Horizontal layers
- (b) Dyke/Sill intrusion

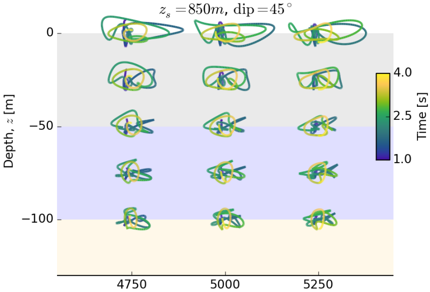


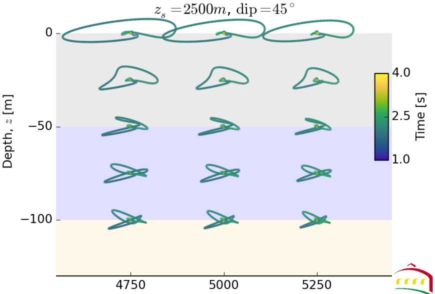
- Source locations matrix (point sources)
- Source strike and dip variation
- Magnitude variations
- Range of frequencies



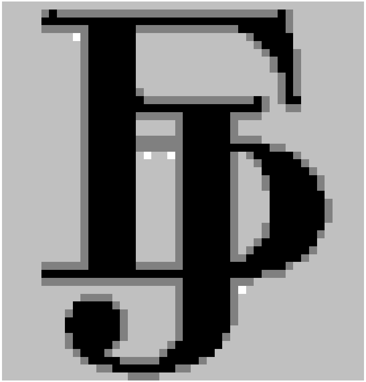
Layered System, Displacement Traces

- Epicenter is 2500m away from the location of interest
- Source depth 850m (left) and 2500m (right)
- Different wave propagation path to the point of interest
- Surface waves quite pronounced
- Layered geology did not filter out surface waves





Layered System, Variable Source Depth



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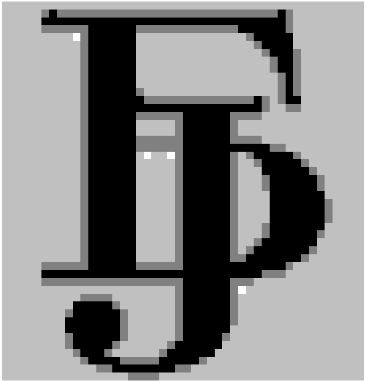

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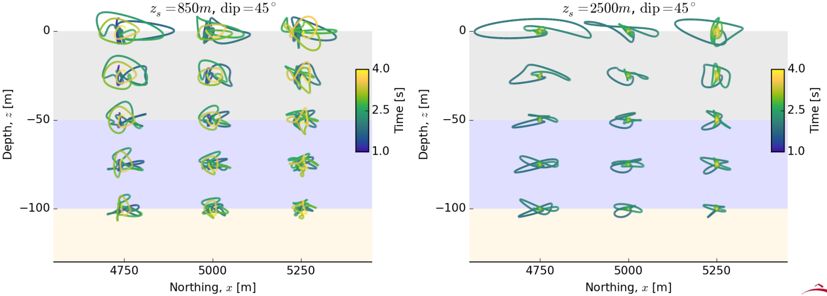
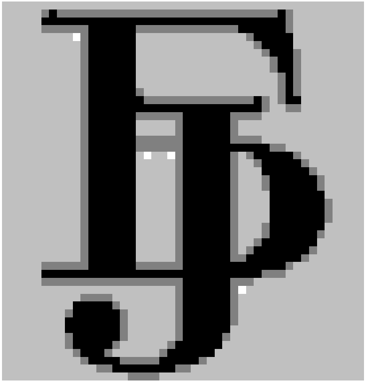
Dyke/Sill Intrusion, Variable Source Depth

- Lower amplitudes than with layered only model!
- Difference in body and surface wave arrivals
- Surface waves present, more complicated wave field



Dyke/Sill Intrusion, Variable Source Depth



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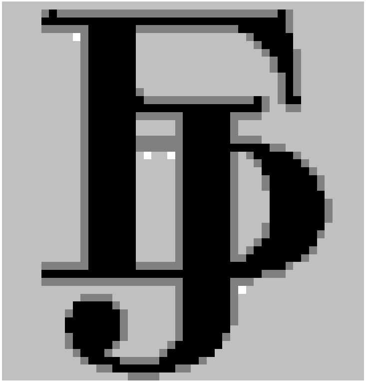

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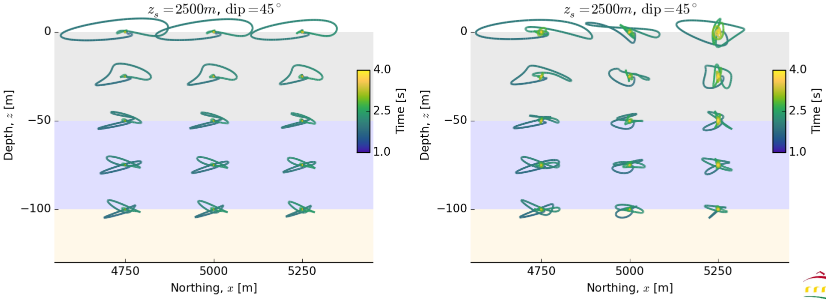
Dyke/Sill as Seismic Energy Sink

- Dyke/Sill (right Fig), made of stiff rock, is an energy sink, as well as energy reflector
- Variable wave lengths behave differently, depending on dyke/sill geometry and location



Outline

Energy Input and Dissipation

- Energy input, dynamic forcing
- Mechanical dissipation outside SSI domain:
  - SSI system oscillation radiation
  - Reflected wave radiation
- Mechanical dissipation/conversion inside SSI domain:
  - Inelasticity of soil and contact zone
  - Inelasticity/damage of structure and foundation
  - Viscous coupling of porous solid and pore fluids (soil)
  - Viscous coupling of structures with fluids
- Numerical energy dissipation/production

Fully Coupled Formulation, u-p-U

$$\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix} \begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_N \\ \ddot{\bar{U}}_{Lj} \end{bmatrix} + \begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix} \begin{bmatrix} \dot{\bar{u}}_{Lj} \\ \dot{\bar{p}}_N \\ \dot{\bar{U}}_{Lj} \end{bmatrix}$$

$$+ \begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\ -(G_1)_{LjM} & -P_{MN} & -(G_2)_{LjM} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix} \begin{bmatrix} \bar{u}_{Lj} \\ \bar{p}_M \\ \bar{U}_{Lj} \end{bmatrix} = \begin{bmatrix} \bar{f}_{Ki}^{solid} \\ 0 \\ \bar{f}_{Ki}^{fluid} \end{bmatrix}$$

Fully Coupled Formulation, u-p-U

$$(M_s)_{KijL} = \int_\Omega H_K^u (1-n)\rho_s \delta_{ij} H_L^u d\Omega \quad (M_f)_{KijL} = \int_\Omega H_K^U n \rho_f \delta_{ij} H_L^U d\Omega$$

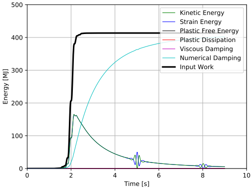
$$(C_1)_{KijL} = \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^u d\Omega \quad (C_2)_{KijL} = \int_\Omega H_K^u n^2 k_{ij}^{-1} H_L^U d\Omega$$

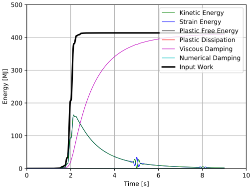
$$(C_3)_{KijL} = \int_\Omega H_K^U n^2 k_{ij}^{-1} H_L^U d\Omega \quad (K^{EP})_{KijL} = \int_\Omega H_{K,m}^u D_{imjn} H_{L,n}^u d\Omega$$

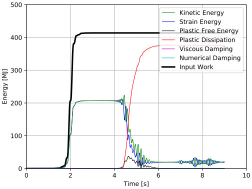
$$(G_1)_{KiM} = \int_\Omega H_{K,i}^u (\alpha - n) H_M^p d\Omega \quad (G_2)_{KiM} = \int_\Omega n H_{K,i}^U H_M^p d\Omega$$

$$P_{NM} = \int_\Omega H_N^p \frac{1}{Q} H_M^p d\Omega$$

Energy Dissipation Control Mechanisms

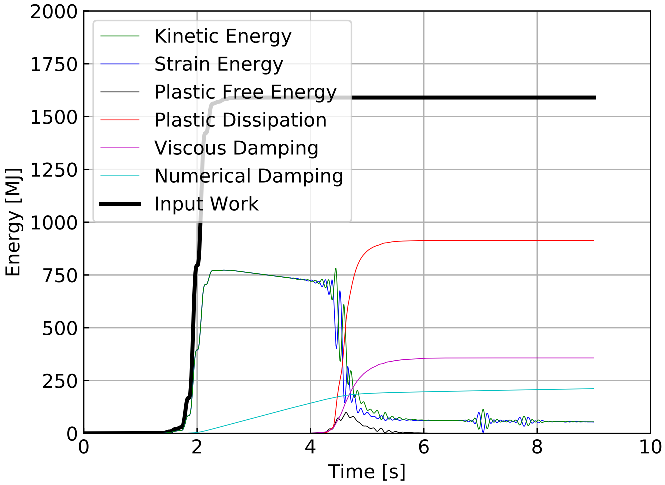






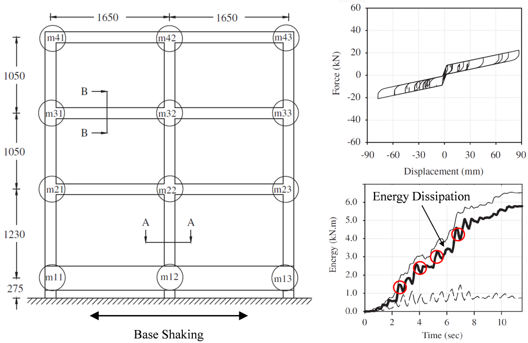
Numerical Viscous Plasticity

Energy Dissipation Control



Incremental Plastic Work: $dW_p = \sigma_{ij}\, d\epsilon_{ij}^{pl}$

- Negative incremental energy dissipation
- Plastic work is NOT plastic dissipation



From a paper on *Soil Dynamics and Earthquake Engineering* (2011)

Negative Incremental Energy Dissipation!

Direct violation of the second law of thermodynamics

600 papers since 1990 (!?!) repeat this error

Important form of energy missing: Plastic Free Energy

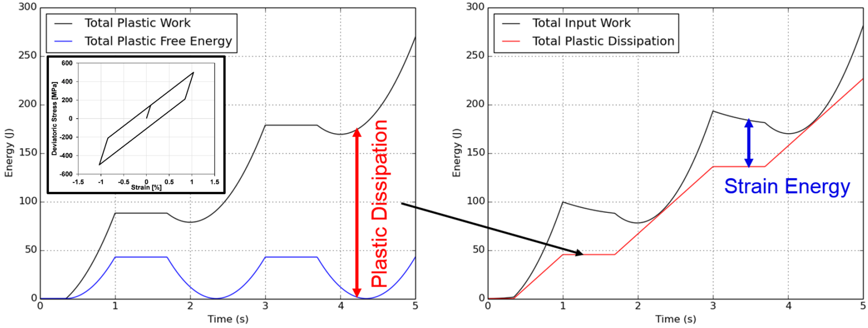
First described by Taylor and Quinney in 1925 and then 1934!

Plastic Work vs. Plastic Energy Dissipation

Energy Dissipation on Material Level

Single elastic-plastic element under cyclic shear loading

- Difference between plastic work and dissipation
- Plastic work can decrease, dissipation always increases



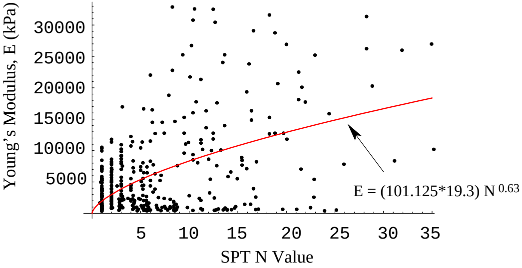
Energy Dissipation for Soil Structure Systems

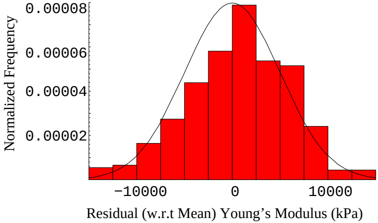
Examples of energy dissipation for buildings (nuclear power plants and small modular reactors) are given in section on ESSI modeling and simulation.

Outline

Parametric Uncertainty: Material and Loads

- Significant uncertainty in material and loads
- Propagate uncertainties in space and time





Transformation of SPT *N*-value: 1-D Young's modulus, *E* (cf. Phoon and Kulhawy (1999B))

Stochastic Elastic-Plastic Finite Element Method (SEPFEM)

Material uncertainty expanded along stochastic shape functions: $D(x,t,\theta) = \sum_{i=0}^{P_d} r_i(x,t) * \Phi_i[\{\xi_1, ..., \xi_m\}]$

Loading uncertainty expanded along stochastic shape functions: $f(x,t,\theta) = \sum_{i=0}^{P_f} f_i(x,t) * \zeta_i[\{\xi_{m+1}, ..., \xi_f\}]$

Displacement expanded along stochastic shape functions: $u(x,t,\theta) = \sum_{i=0}^{P_u} u_i(x,t) * \Psi_i[\{\xi_1, ..., \xi_m, \xi_{m+1}, ..., \xi_f\}]$

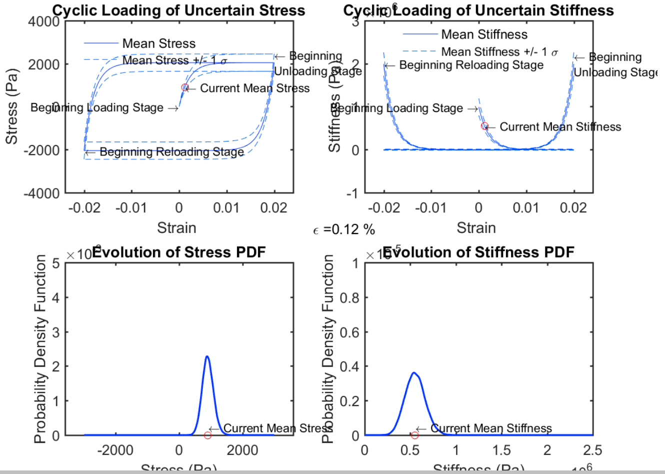
SEPFEM : Formulation

Stochastic system of equation resulting from Galerkin approach

$$\begin{bmatrix} \sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_0 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_0 > K^{(k)} \\ \sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_1 > K^{(k)} & \dots & \sum_{k=0}^{P_d} < \Phi_k \Psi_P \Psi_1 > K^{(k)} \\ \vdots & \vdots & \vdots \\ \sum_{k=0}^{P_d} < \Phi_k \Psi_0 \Psi_P > K^{(k)} & \dots & \sum_{k=0}^{M} < \Phi_k \Psi_P \Psi_P > K^{(k)} \end{bmatrix} \begin{bmatrix} u_{10} \\ \vdots \\ u_{N0} \\ \vdots \\ u_{1P_u} \\ \vdots \\ u_{NP_u} \end{bmatrix} = \begin{bmatrix} \sum_{i=0}^{P_f} f_i < \Psi_0 \zeta_i > \\ \sum_{i=0}^{P_f} f_i < \Psi_1 \zeta_i > \\ \sum_{i=0}^{P_f} f_i < \Psi_2 \zeta_i > \\ \vdots \\ \sum_{i=0}^{P_f} f_i < \Psi_{P_u} \zeta_i > \end{bmatrix}$$

# KL terms material	# KL terms load	PC order displacement	Total # terms per DoF
4	4	10	43758
4	4	20	3 108 105
4	4	30	48 903 492
6	6	10	646 646
6	6	20	225 792 840
6	6	30	$1.1058\ 10^{10}$
...	...	...	...

SEPFEM : Probabilistic Elastic-Plastic Modeling



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SEPFEM : Example in 1D

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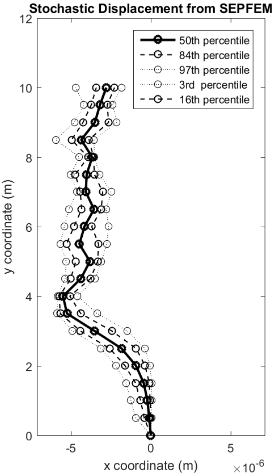
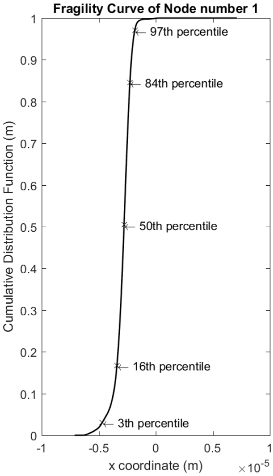
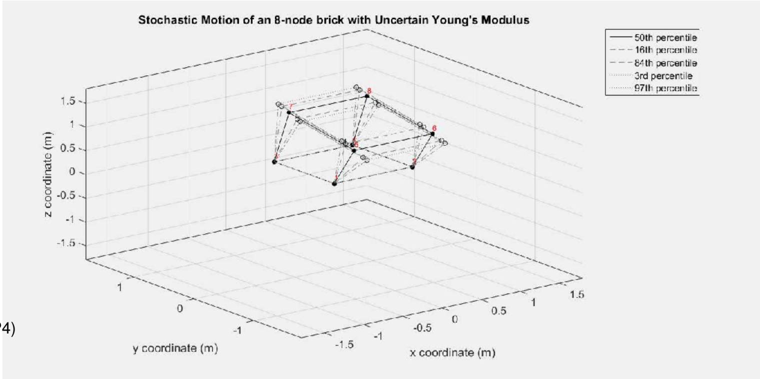




SEPFEM : Example in 3D



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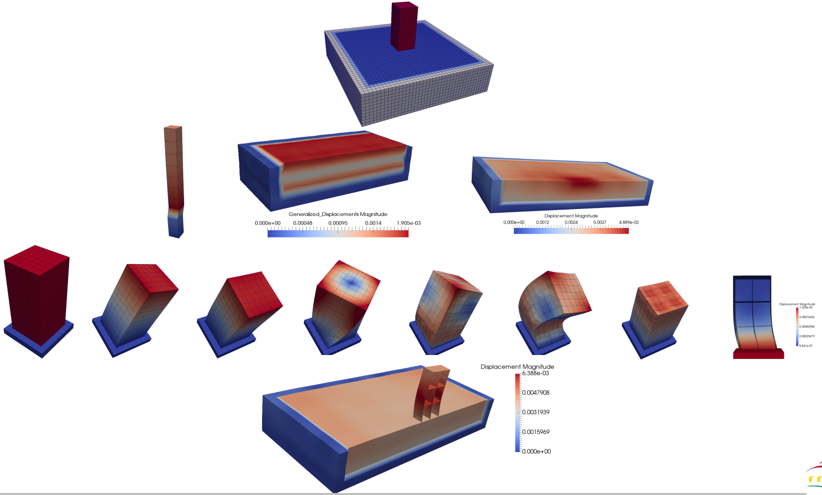
Outline

Modeling Sophistication Levels, Phased Modeling

- Level of sophistication chosen to reduce modeling uncertainty
- Verify code, solutions, methods, elements, material models
- Verify model components
- Model developed in phases (components) and verified
- Gradually building confidence in inelastic modeling
- Use such developed models to predict and inform, rather than force fit

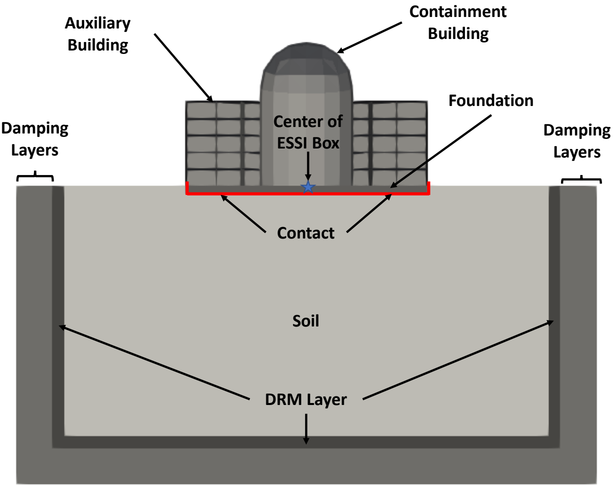
Model Verification and Modeling Phases



Inelastic Modeling for NPP and Components

- Soil elastic-plastic
  - Dry, single phase
  - Unsaturated (partially saturated)
  - Fully saturated
- Contact, inelastic, soil/rock – foundation
  - Dry, single phase, Normal (hard and soft, gap open/close), Friction (nonlinear)
  - Fully saturated, suction and excess pressure (buoyant force)
- Structural inelasticity/damage
  - Nonlinear/inelastic 1D fiber beam
  - Nonlinear/inelastic 2D wall element

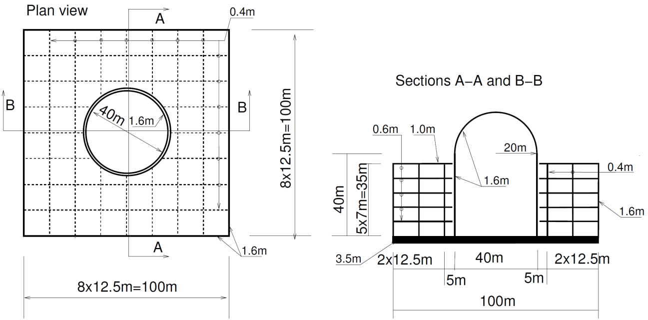
NPP Model


Auxiliary Building
Containment Building
Foundation
Damping Layers
Center of ESSI Box
Damping Layers
Contact
Soil
DRM Layer

Structure Model

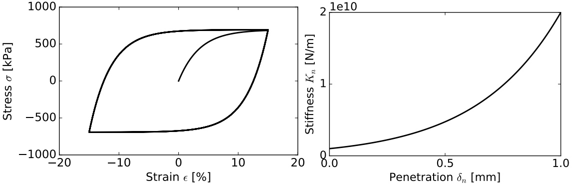
The nuclear power plant structure comprise of

- Auxiliary building, $f_1^{aux} = 8Hz$
- Containment/Shield building, $f_1^{cont} = 4Hz$
- Concrete raft foundation: 3.5m thick

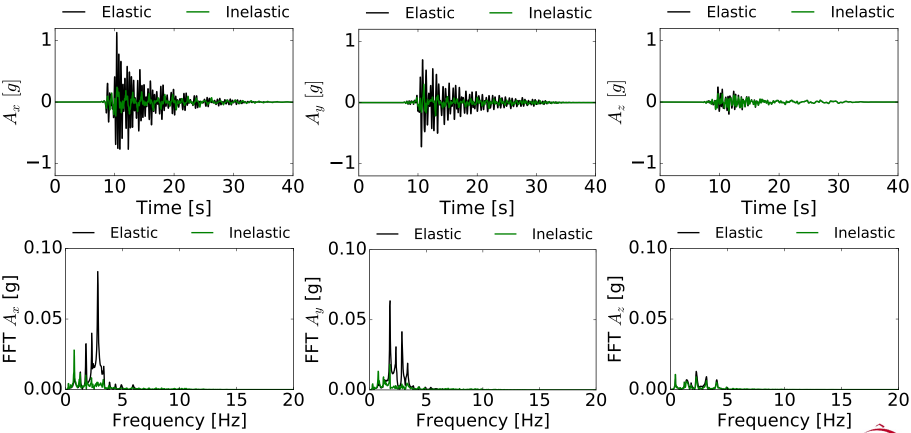


Inelastic Soil and Inelastic Contact

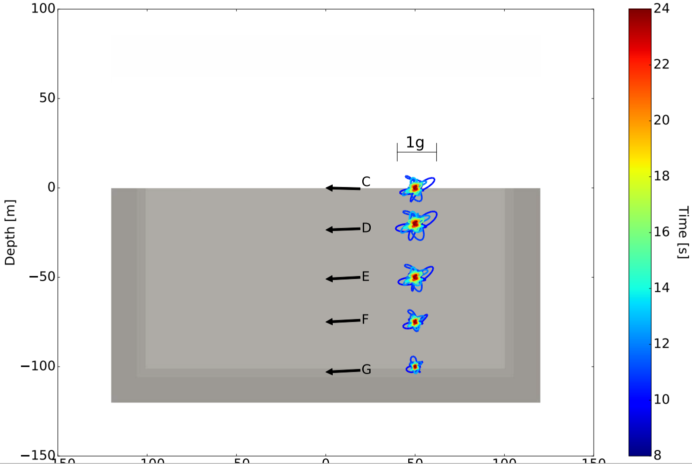
- Shear velocity of soil $V_s = 500 m/s$
- Undrained shear strength (Dickenson 1994) $V_s[m/s] = 23(S_u[kPa])^{0.475}$
- For $V_s = 500 m/s$ Undrained Strength $S_u = 650 kPa$ and Young's Modulus of $E = 1.3 GPa$
- von Mises, Armstrong Frederick kinematic hardening ($S_u = 650 kPa$ at $\gamma = 0.01\%$; $h_a = 30 MPa$, $c_r = 25$)
- Soft contact (concrete-soil), gaping and nonlinear shear



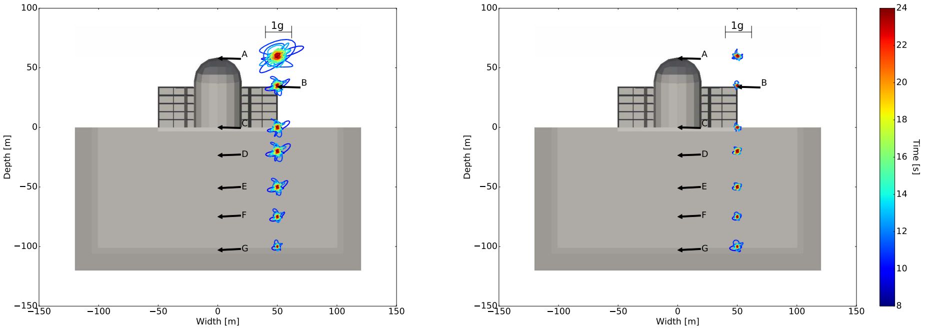
Acc. Response, Top of Containment Building



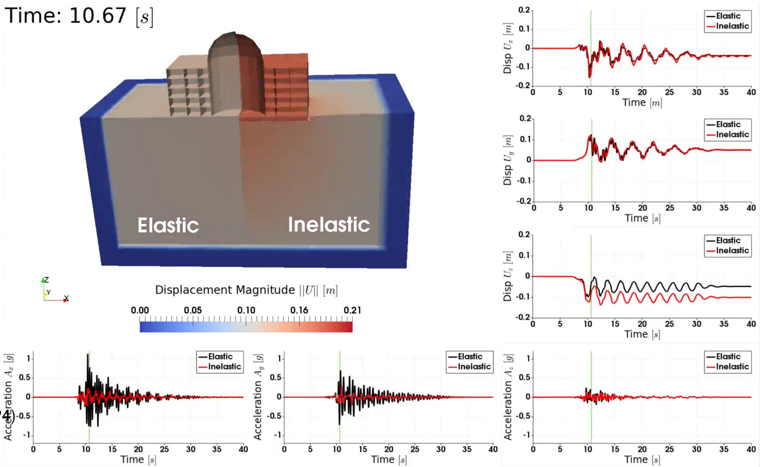
Acceleration Traces, Free Field



Acceleration Traces, Elastic vs Inelastic

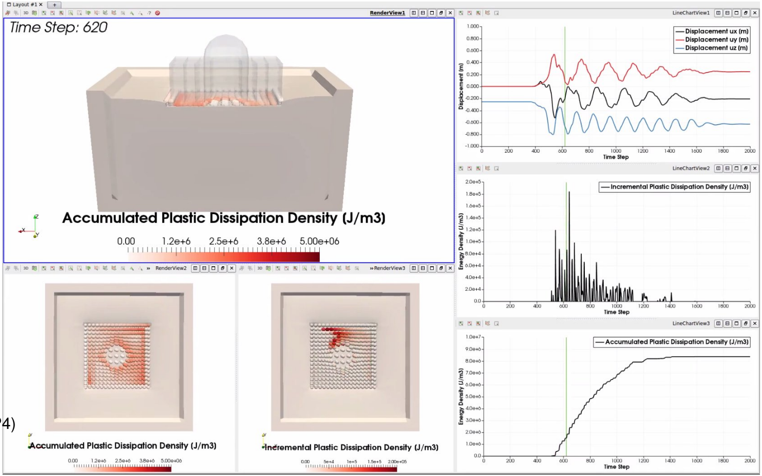


Elastic and Inelastic Response: Differences



(MP4)

Energy Dissipation in Large-Scale Model (NPP)



(MP4)

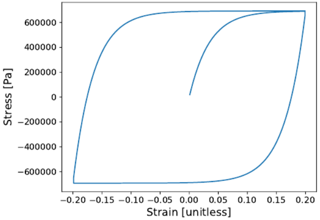
Outline

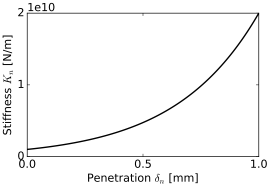
Inelastic Modeling for Components

- Soil elastic-plastic
  - Dry, single phase
  - Unsaturated (partially saturated)
  - Fully saturated
- Contact, inelastic, soil/rock – foundation
  - Dry, single phase, Normal (hard and soft, gap open/close), Friction (nonlinear)
  - Fully saturated, suction and excess pressure (buoyant force)
- Structural inelasticity/damage
  - Nonlinear/inelastic 1D fiber beam
  - Nonlinear/inelastic 2D wall element

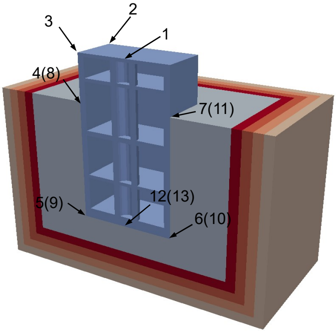
Soil Modeling Parameters

Material parameters	shear wave velocity [m/s]	500
	Young's modulus [GPa]	1.25
	Poisson ratio	0.25
	von Mises radius [kPa]	60
	linear hardening parameter [MPa]	30
	nonlinear hardening parameter	25
Contact parameters	initial normal stiffness [N/m]	1e9
	hardening rate [/m]	1000
	maximum normal stiffness [N/m]	1e12
	tangential stiffness [N/m]	1e7
	normal damping [N/(m/s)]	100
	tangential damping [N/(m/s)]	100
	friction ratio	0.25
Damping parameters	structure layer	5%
	surrounding soil	15%
	DRM layer	20%
	outside layer 1	20%
	outside layer 2	40%
	outside layer 3	60%





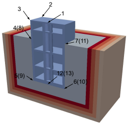
Representative points

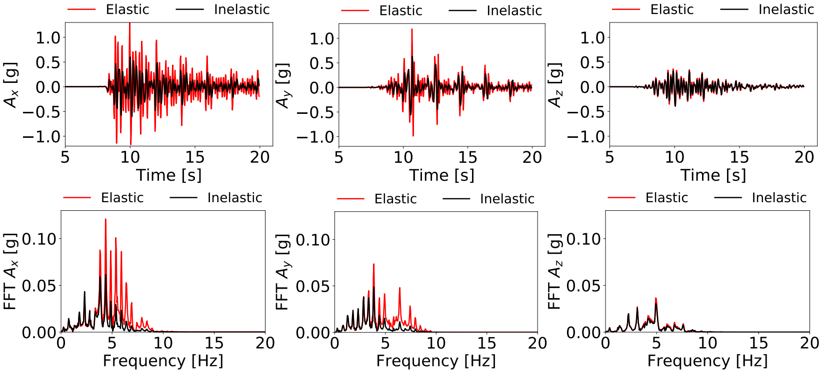


Location of points

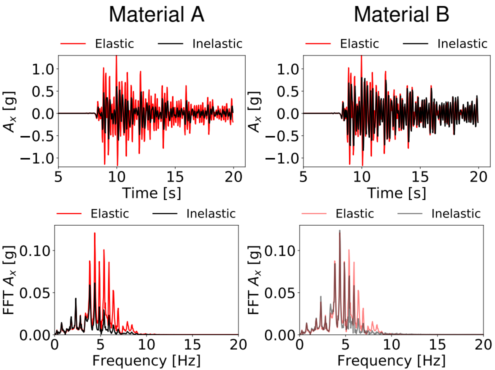
Point ID	X (m)	Y (m)	Z (m)	layer
1	0	0	14	structure
2	15	15	14	structure
3	0	15	14	structure
4	0	15	0	structure
5	0	15	-36	structure
6	0	-15	-36	structure
7	0	-15	0	structure
8	0	15	0	surrounding soil
9	0	15	-36	surrounding soil
10	0	-15	-36	surrounding soil
11	0	-15	0	surrounding soil
12	0	0	-36	structure
13	0	0	-36	surrounding soil

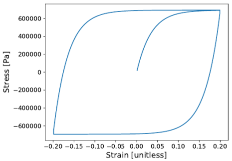
SMR: Inelastic ESSI Effects, Top Center



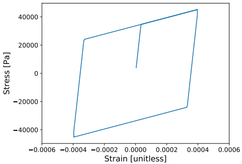


SMR: ESSI Effects, Material Modeling



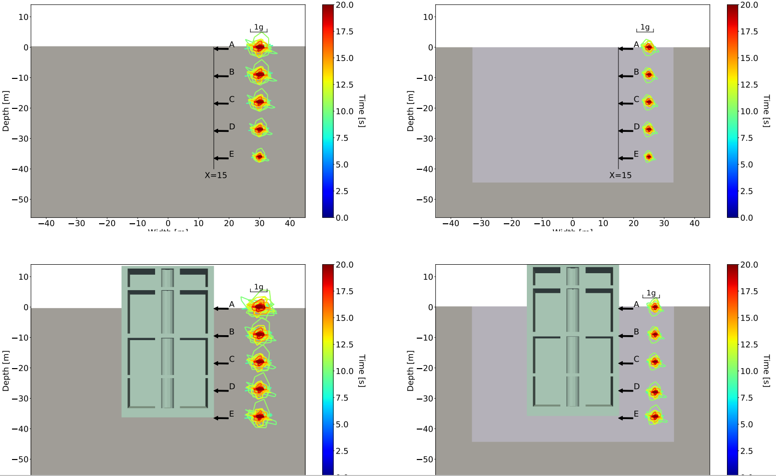


Material A: nonlinear, vM - AF



Material B: Bilinear

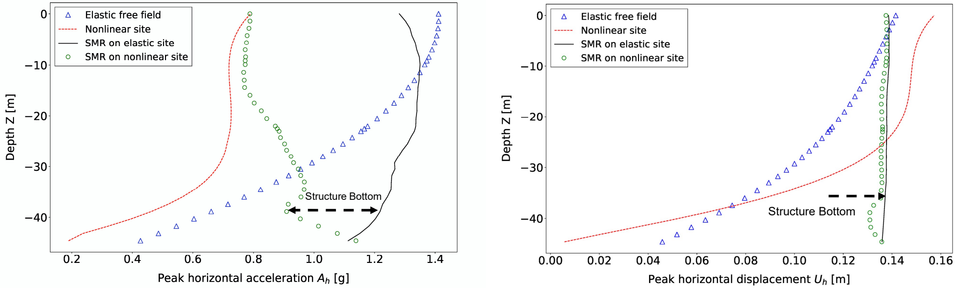
SMR: Accelerations Along Depth



Nonlinear site effects

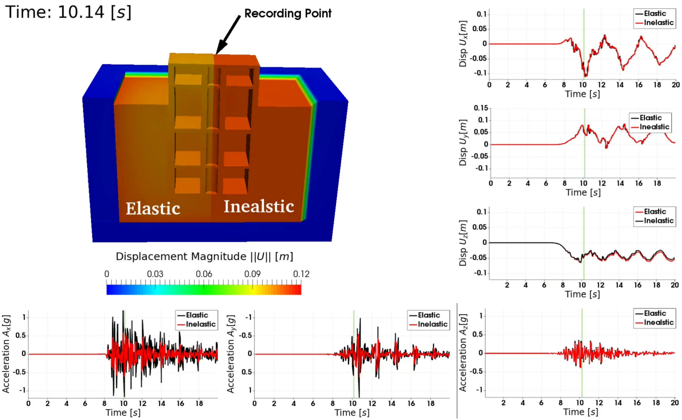
SSI effects

Depth variation - PGA & PGD



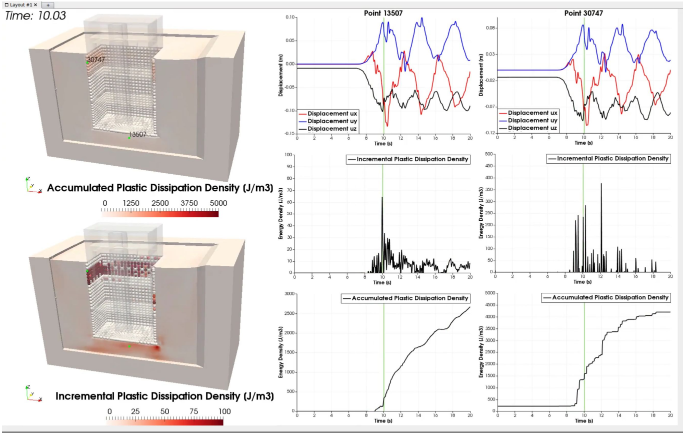
- The PGA & PGD of SSI systems are (very) different from free field motions,
- Material nonlinearity has significant effect on acceleration response.

Elastic and Inelastic Response: Differences



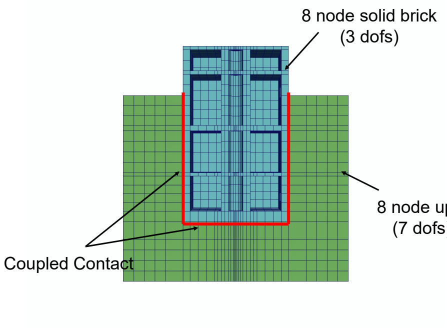
(MP4)

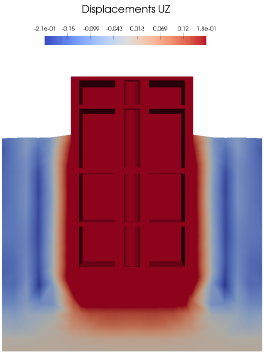
Energy Dissipation for an SMR



(MP4)

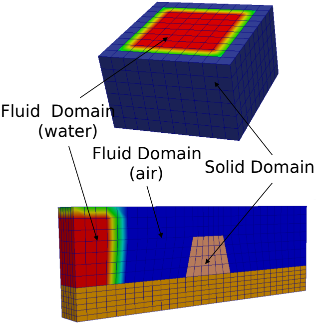
Buoyant Force Simulation



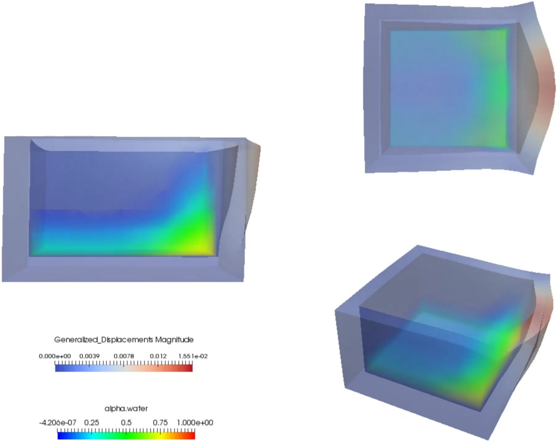


Solid/Structure-Fluid Interaction: gmFoam

- Mesh separation
  - integrated geometry model
  - FEM & FVM mesh conversion
  - handle discontinuous mesh
- Incorporate gmESSI
- Interface geometry extraction
- Interface class **SSFI** in RealESSI
- RealESSI $\Longleftrightarrow$ SSFI $\Longleftrightarrow$ OpenFoam



Solid/Structure-Fluid Interaction, Example



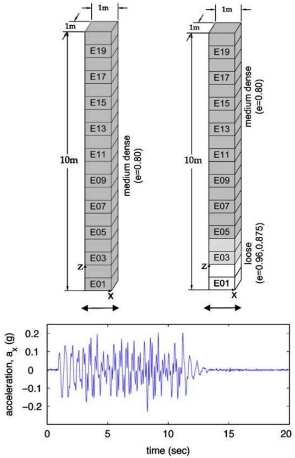
(MP4)

Outline

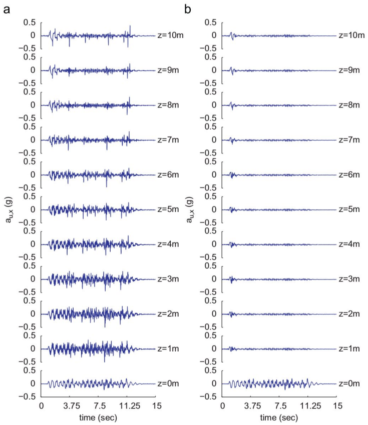
Saturated Soil

- For fully and partially saturated layers of loose to medium sand, with fines, silt, and with in-between layers of low permeability clay, liquefaction is likely
- Liquefaction can result in uniform and differential settlements!
- Liquefaction can also base isolate objects
  (Mahdi Taiebat, Boris Jeremic. Yannis F. Dafalias, Amir M. Kaynia, and Zhao Cheng. Propagation of Seismic Waves through Liquefied Soils. Soil Dynamics and Earthquake Engineering, No. 30, pp 236-257, 2010.)
- Piles in liquefied soil, pile pinning effects
  ((Zhao Cheng and Boris Jeremic. Numerical Simulations of Piles in Liquefied Soils. Soil Dynamics and Earthquake Engineering, No. 29, pp 1405-1416, 2009.)

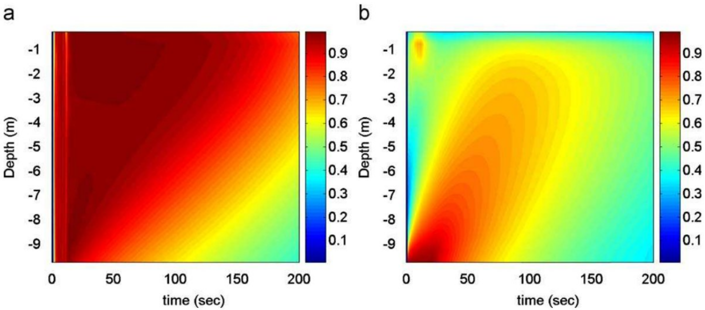
Liquefaction as Base Isolation, Model



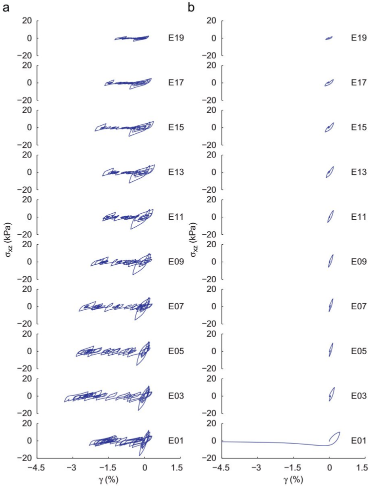
Liquefaction, Wave Propagation



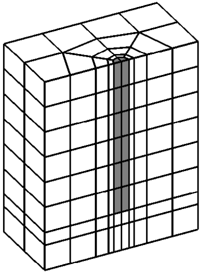
Liquefaction, Excess Pore Pressure Ratio

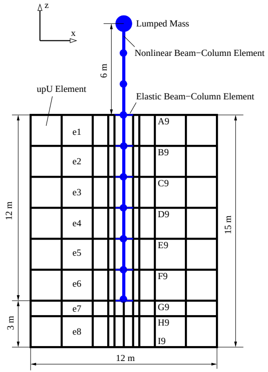


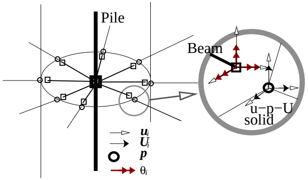
Liquefaction, Stress-Strain Response



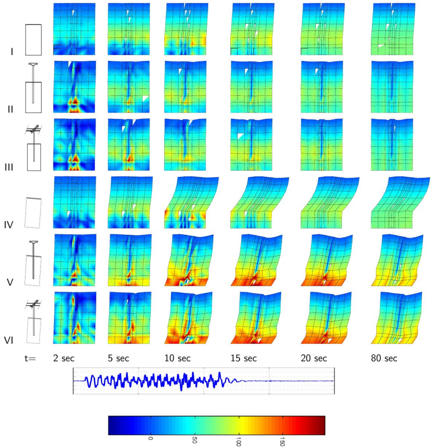
Pile in Liquefiable Soil, Model







Pile in Liquefiable Soil, Results



Summary

- Numerical modeling to predict and inform, rather than fit
- Sophisticated inelastic/nonlinear modeling and simulations need to be done carefully and in phases
- Education and Training is the key!
- `http://real-essi.us/`
- Collaborators: Feng, Lacour, Han, Behbehani, Sinha, Wang, Pisanó, Abell, McCallen, McKenna, Petrone, Rodgers, Petersson, Pitarka
- Funding from and collaboration with the US-DOE, US-NRC, US-NSF, CNSC-CCSN, UN-IAEA, and Shimizu Corp. is greatly appreciated,